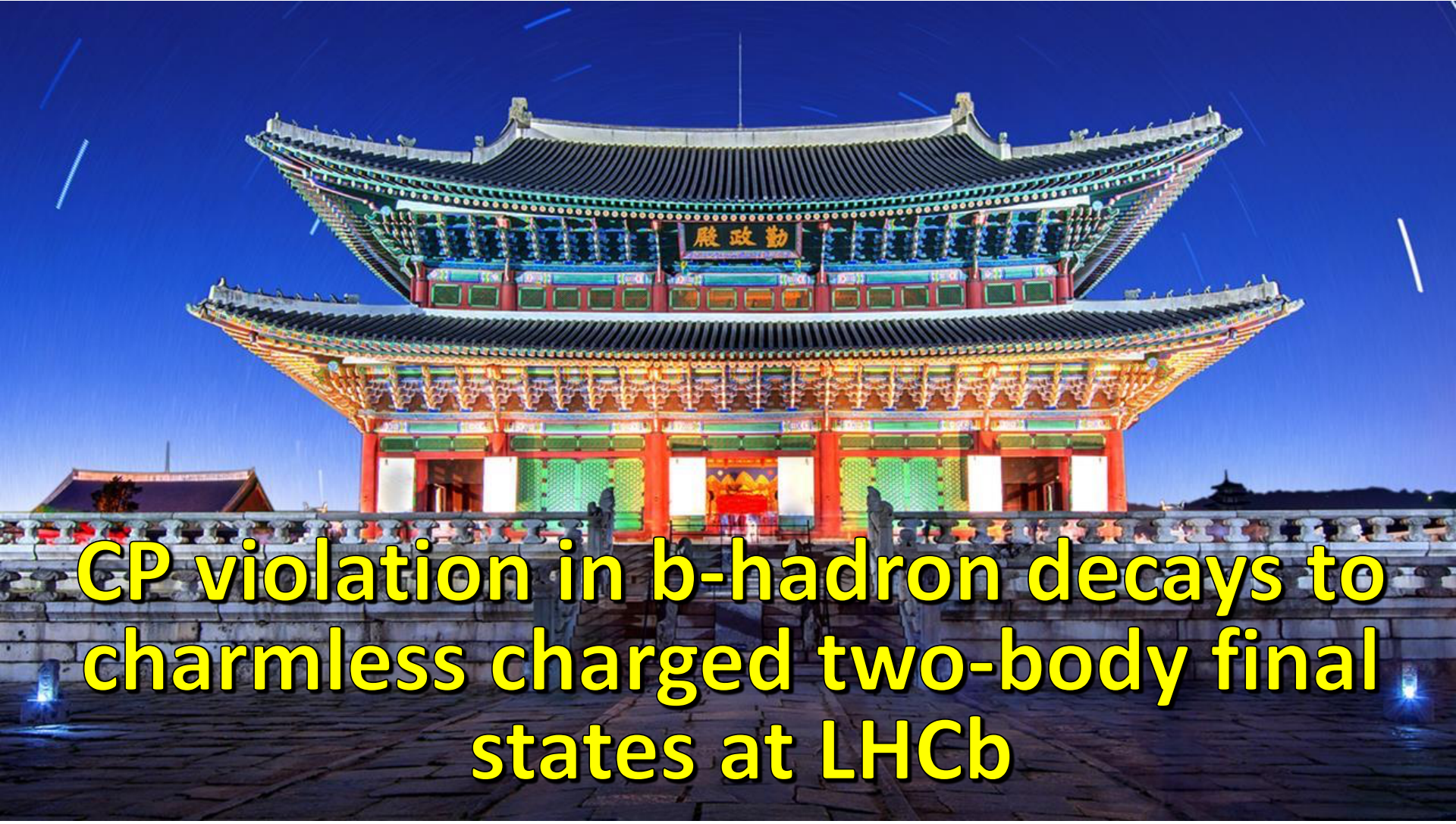


CP violation in b-hadron decays to charmless charged two-body final states at LHCb

Stefano Perazzini, on behalf of LHCb Collaboration
CERN & INFN Bologna

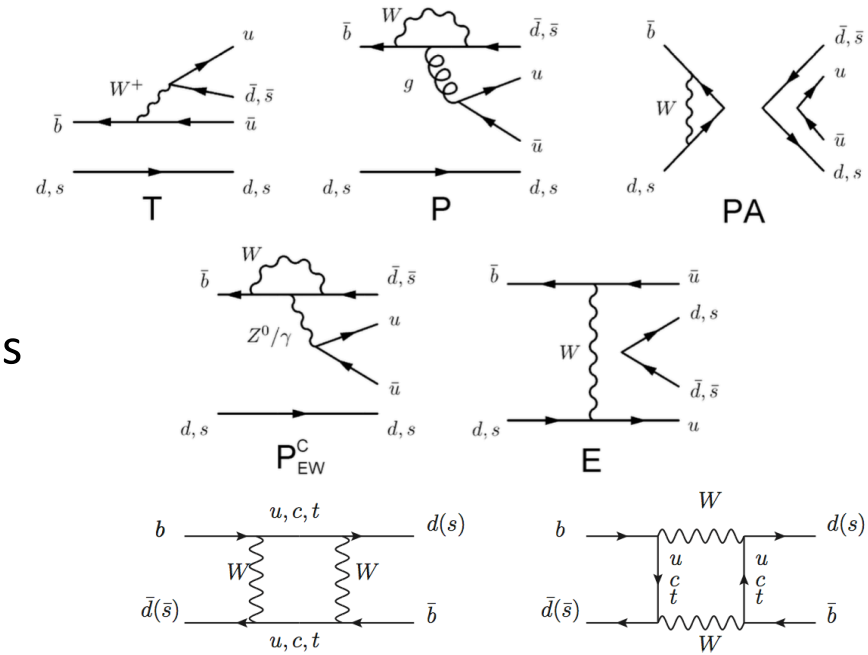
XXXIX International Conference on High Energy Physics – Seoul, 6th July 2018

Outline

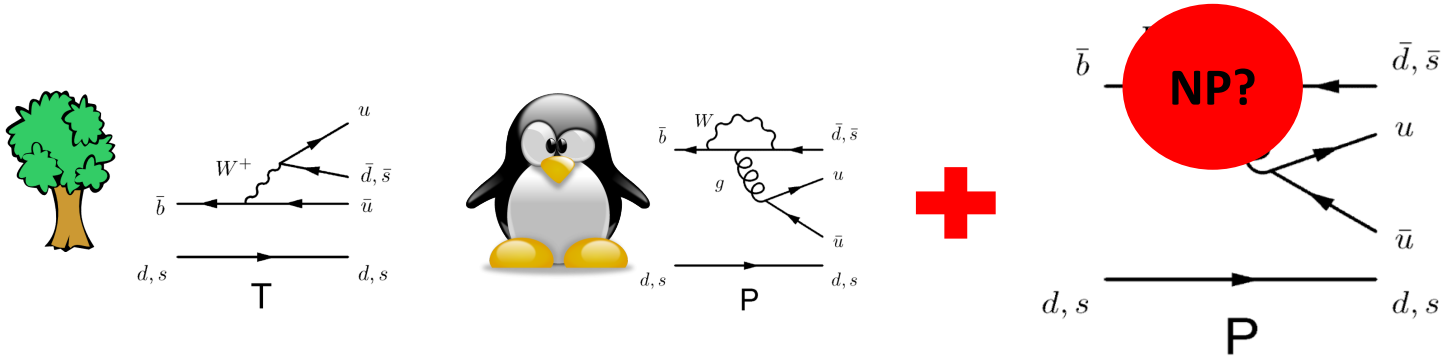
- Motivations, CPV observables and current experimental status
- Main ingredients of presented analyses:
  - Measurement of CP asymmetries in two-body $B^0_{(s)}$-meson decays to charged pions and kaons
    [arXiv:1805.06759 – submitted to PRD]
  - Search for CPV in $\Lambda_b^0 \rightarrow pK^-$ and $\Lambda_b^0 \rightarrow p\pi^-$ decays
    [LHCb-PAPER-2018-025 – will appear soon on arXiv]
- Conclusions

Motivation

- A rich set of physics processes participates in the $H_b \rightarrow h^+h'^-$ decays
  - Tree and penguin decay topologies
  - Neutral B mixing
- CPV observables are sensitive to CKM angles γ and α and mixing phases ϕ_s and ϕ_d
  - presence of loop diagrams introduces hadronic uncertainties
  - presence of loop diagrams makes the CPV observables sensitive to New Physics contributions



[PLB459(1999)306, PLB621(2005)126, PJC71(2011)1532, JHEP 10 (2012) 029, PLB741(2015)1, PRD94(2016)113014, EPJ C77(2017)574, JHEP03(2017)55]



CPV observable

- Time-dependent CPV asymmetries ($B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$)

$$\mathcal{A}(t) = \frac{\Gamma_{\bar{B}^0_{(s)}\to f}(t) - \Gamma_{B^0_{(s)}\to f}(t)}{\Gamma_{\bar{B}^0_{(s)}\to f}(t) + \Gamma_{B^0_{(s)}\to f}(t)} = \frac{-C_f \cos\left(\Delta m_{d(s)} t\right) + S_f \sin\left(\Delta m_{d(s)} t\right)}{\cosh\left(\frac{\Delta\Gamma_{d(s)}}{2} t\right) + A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_{d(s)}}{2} t\right)}$$

$$C_f = \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2}$$

CPV in the decay

$$S_f = \frac{2\mathrm{Im}\lambda_f}{|\lambda_f|^2 + 1}$$

CPV from mixing/decay interference

Condition not imposed

$$\left|C_f\right|^2 + \left|S_f\right|^2 + \left|A_f^{\Delta\Gamma}\right|^2 = 1$$

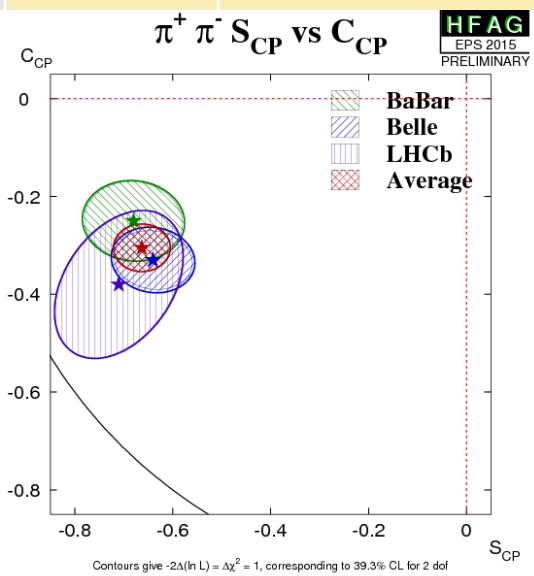
- Time-integrated CPV asymmetries ($B^0 \to K^+\pi^-$, $B_s^0 \to \pi^+K^-$, $\Lambda_b^0 \to pK^-$ and $\Lambda_b^0 \to p\pi^-$)

$$A_{CP} = \frac{\left|\bar{A}_{\bar{f}}\right|^2 - \left|A_f\right|^2}{\left|\bar{A}_{\bar{f}}\right|^2 + \left|A_f\right|^2},$$

Current status (TD CPV)

$B^0 \rightarrow \pi^+\pi^-$

Experiment	S_{CP} ($\pi^+\pi^-$)	C_{CP} ($\pi^+\pi^-$)	Correlation	Reference
BaBar N(BB)=467M	$-0.68 \pm 0.10 \pm 0.03$	$-0.25 \pm 0.08 \pm 0.02$	-0.06 (stat)	PRD 87 (2013) 052009
Belle N(BB)=772M	$-0.64 \pm 0.08 \pm 0.03$	$-0.33 \pm 0.06 \pm 0.03$	-0.10 (stat)	PRD 88 (2013) 092003
LHCb $\int Ldt$=1.0 fb^{-1}	$-0.71 \pm 0.13 \pm 0.02$	$-0.38 \pm 0.15 \pm 0.02$	0.38 (stat)	JHEP 1310 (2013) 183
Average	-0.66 ± 0.06	-0.31 ± 0.05	0.00	HFAG correlated average χ^2 = 0.9/4 dof (CL=0.92 ⇒ 0.1σ)



- $C_{\pi\pi}$ and $S_{\pi\pi}$ are well constrained by B-factories and LHCb
  - All three experiments are in good agreement
- C_{KK} and S_{KK} are measured only by LHCb using 1 fb^{-1} @ 7 TeV
  - No measurement is available for $A_{KK}^{\Delta\Gamma}$

JHEP 1310 (2013) 183 – $B_s^0 \rightarrow K^+K^-$

$$C_{KK} = 0.14 \pm 0.11\,(\text{stat}) \pm 0.03\,(\text{syst}),$$

$$S_{KK} = 0.30 \pm 0.12\,(\text{stat}) \pm 0.04\,(\text{syst}),$$

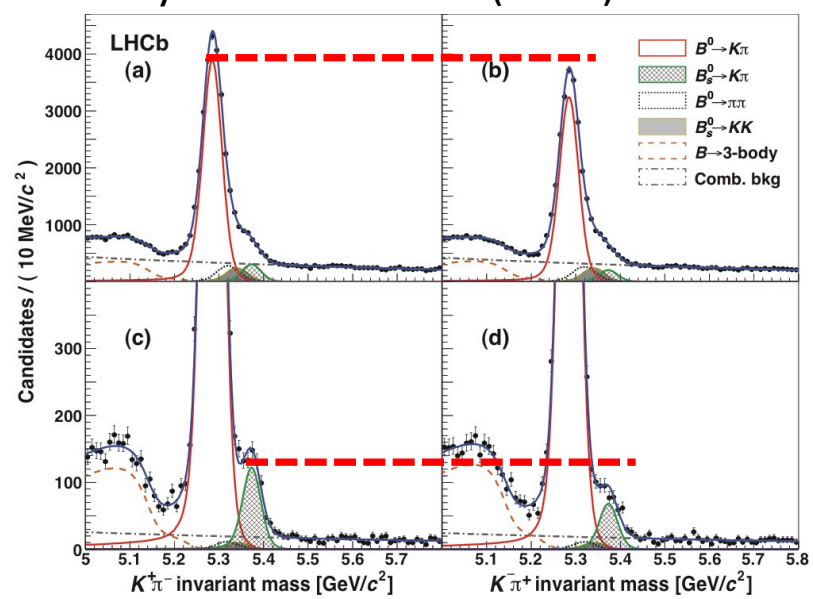
Current status (TI CPV)

- Direct CPV in $B^0 \rightarrow K^+\pi^-$ and $B_s^0 \rightarrow \pi^+K^-$ are dominated by LHCb measurement (with L = 1 fb^{-1}) [Phys. Rev. Lett. 110 (2013) 221601]
- Direct CPV in $\Lambda_b^0 \rightarrow pK^-$ and $\Lambda_b^0 \rightarrow p\pi^-$ have been measured only by CDF so far [Phys. Rev. Lett. 113 242001 (2014)]

BaBar: PRD87(2013)052009; Belle: PRD87(2013)031103;
CDF: PRL113(2014)242001

Experiment	$A_{CP}(B^0 \rightarrow K^+\pi^-)$	$A_{CP}(B_s^0 \rightarrow \pi^+K^-)$
BaBar	$-0.107 \pm 0.016 \,^{+0.006}_{-0.004}$	–
Belle	$-0.069 \pm 0.014 \pm 0.007$	–
CDF	$-0.083 \pm 0.013 \pm 0.004$	$0.22 \pm 0.07 \pm 0.02$
LHCb	$-0.080 \pm 0.007 \pm 0.003$	$0.27 \pm 0.04 \pm 0.01$
HFLAV average	-0.082 ± 0.006	0.26 ± 0.04

Phys. Rev. Lett. 110 (2013) 221601



$A_{CP}(\Lambda_b^0 \rightarrow pK^-) = -0.10 \pm 0.08$ (stat.) ± 0.04 (syst.)

$A_{CP}(\Lambda_b^0 \rightarrow p\pi^-) = +0.06 \pm 0.07$ (stat.) ± 0.03 (syst.)

Main experimental ingredients to measure CPV

- Time-integrated CPV:
  - Final-state detection asymmetries (A_F)
  - Production asymmetry (A_P)
    - Thanks to a time-dependent analysis of $B^0 \rightarrow K^+\pi^-$ and $B_s^0 \rightarrow \pi^+K^-$ A_{CP} can be measured already free from A_P
    - For Λ_b^0 decays it is determined by difference with respect to other B species [Phys. Lett. B 774 (2017) 139]

$$A_{exp.} \simeq A_{CP} + A_F + A_P$$

- Time-dependent CPV:
  - Flavour tagging
  - Decay-time resolution
  - Decay-time acceptance

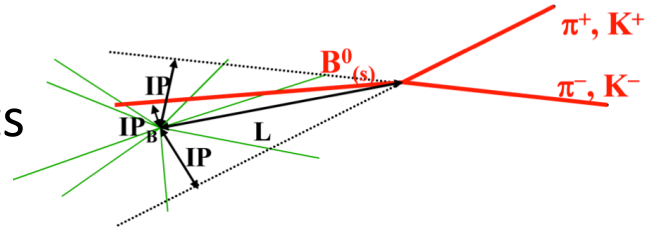
Time res.

$$A_{exp.}(t) \sim (1-2\omega)\, \exp(-\sigma^2_t \Delta m^2/2)\, A(t)$$

Mistag fraction

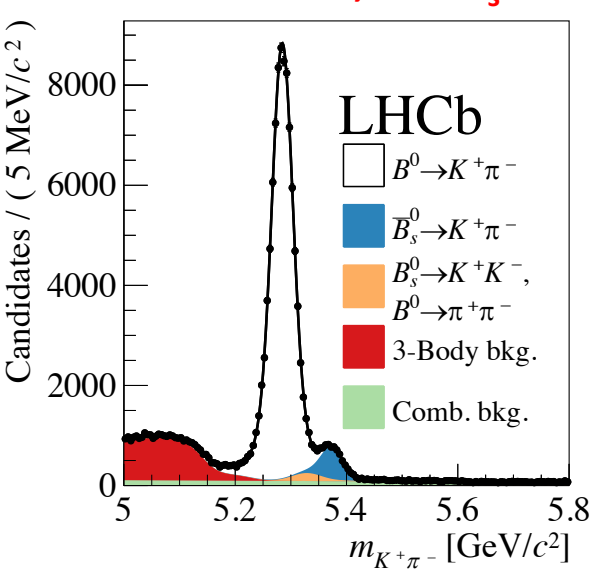
Event selection

- Both analyses are based on the full Run1 statistics
  - 1 fb^{-1} @ 7 TeV + 2 fb^{-1} @ 8 TeV
- Event selection is based on two main ingredients
  - Particle identification
    - Separate the final states and reduce amount of cross contamination from other $H_b \rightarrow h^+h'^-$ modes ➔ Calibrated using $D^{*+} \rightarrow D^0(K^-\pi^+)\pi^+$, $\Lambda \rightarrow p\pi^-$ and $\Lambda_c^+ \rightarrow pK^-\pi^+$
  - MVA algorithm based on BDT to reduce combinatorial background

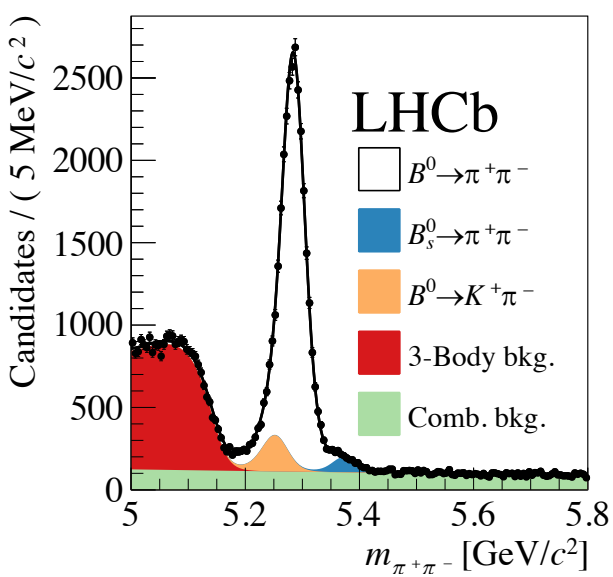


arXiv:1805.06759

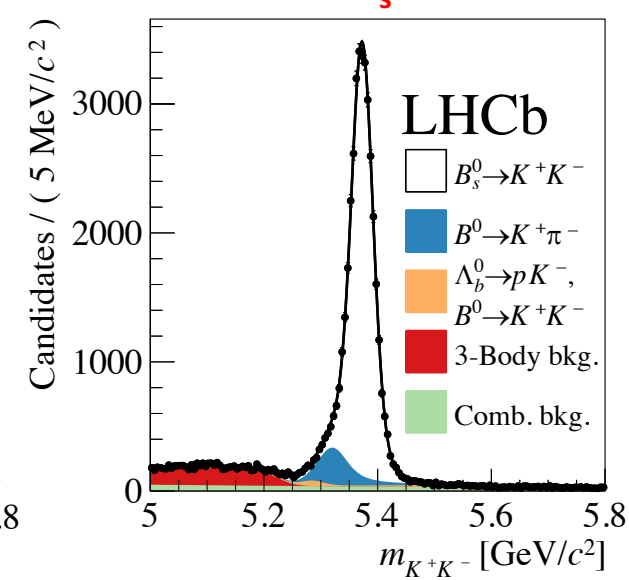
~94k $B^0 \rightarrow K^+\pi^-$; ~7k $B_s^0 \rightarrow \pi^+K^-$



~29k $B^0 \rightarrow \pi^+\pi^-$

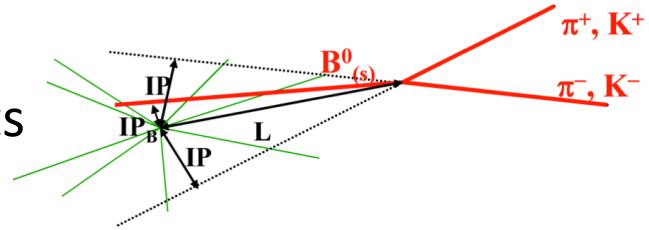


~37k $B_s^0 \rightarrow K^+K^-$

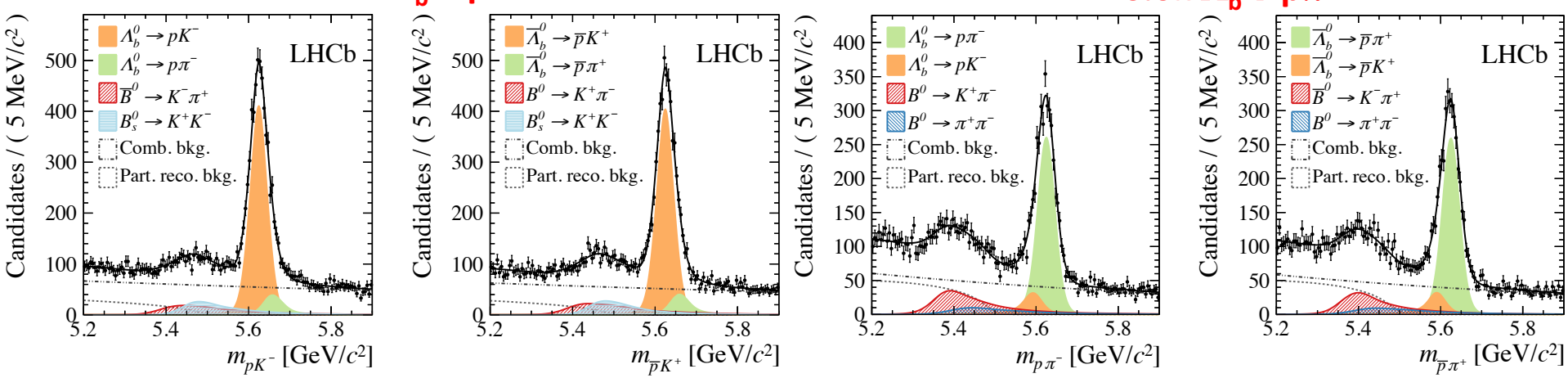


Event selection

- Both analyses are based on the full Run1 statistics
  - 1 fb-1 @ 7 TeV + 2 fb-1 @ 8 TeV
- Event selection is based on two main ingredients
  - Particle identification
    - Separate the final states and reduce amount of cross contamination from other $H_b \rightarrow h^+h'^-$ modes ➔ Calibrated using $D^{*+} \rightarrow D^0(K^-\pi^+)\pi^+$, $\Lambda \rightarrow p\pi^-$ and $\Lambda_c^+ \rightarrow pK^-\pi^+$
  - MVA algorithm based on BDT to reduce combinatorial background



~8.8k $\Lambda_b^0 \rightarrow pK^-$ **~6.0k $\Lambda_b^0 \rightarrow p\pi^-$**



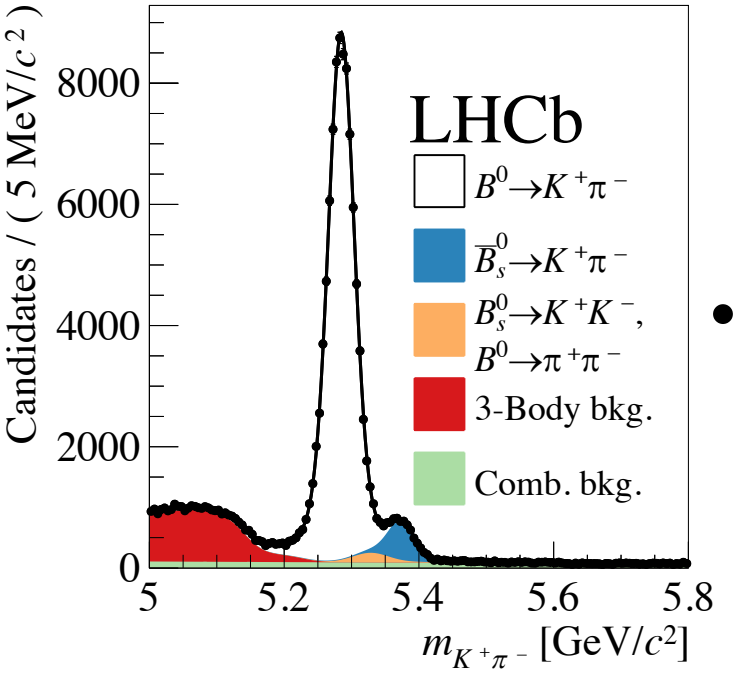
LHCb-PAPER-2018-025 / PRELIMINARY

Final-state detection asymmetry

$$A_F = A_{PID} + A_D$$

- A_{PID} determined using $D^{*+} \rightarrow D^0(K^-\pi^+)\pi^+$, $\Lambda \rightarrow p\pi^-$ and $\Lambda_c^+ \rightarrow pK^-\pi^+$
- A_D for K
  - using raw asymmetries of Cabibbo-Favoured charm decays $D^+ \rightarrow K^-\pi^+\pi^+$ and $D^+ \rightarrow K^0\pi^+$ [JHEP 07 (2014) 041]
- A_D for π
  - from partial reconstruction of $D^{*+} \rightarrow D^0(K^-\pi^+\pi^-\pi^+)\pi^+$ decays [PLB 713 (2012)]
- A_D for p
  - determined from simulation
  - generous systematic assigned due to the assumptions made regarding p/p interaction cross-section

Results



arXiv:1805.06759

$$A_{CP}^{B^0} = -0.084 \pm 0.004 \pm 0.003$$

$$A_{CP}^{B_s^0} = 0.213 \pm 0.015 \pm 0.007$$

- Main syst.:
  - B^0: Det. asymmetry
  - B_s^0: mass model

SM test assuming U-spin validity [PLB621(2005)126]

$$\Delta = \frac{A_{CP}^{B^0}}{A_{CP}^{B_s^0}} + \frac{\mathcal{B}(B_s^0 \to \pi^+K^-)}{\mathcal{B}(B^0 \to K^+\pi^-)}\frac{\tau_d}{\tau_s} = -0.11 \pm 0.04 \pm 0.03$$

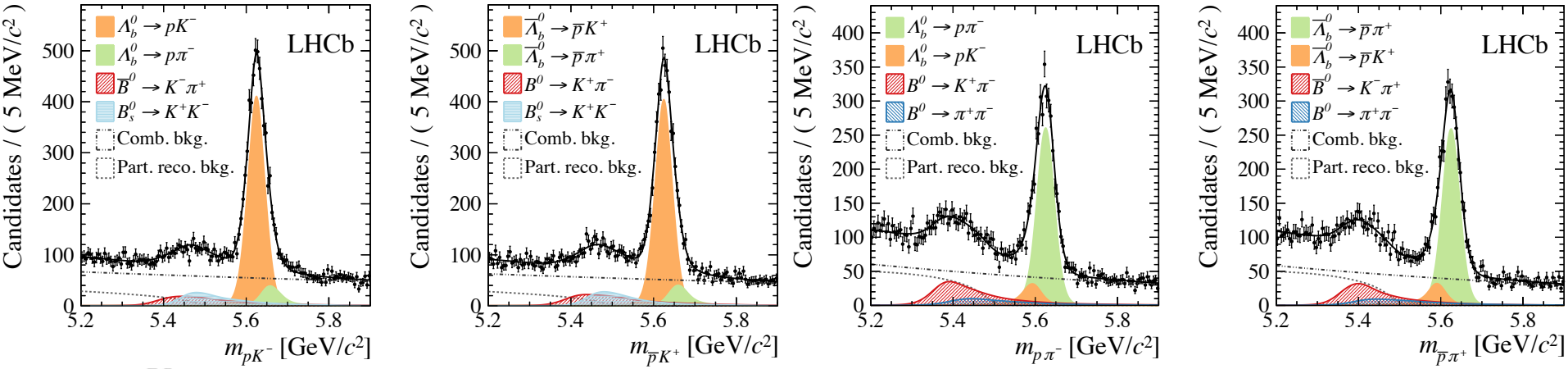
from A_{CP}

- Thanks to the time-dependent analysis the production asymmetries are automatically subtracted
  - $A_P(B^0) = (0.19 \pm 0.60)\%$
  - $A_P(B_s^0) = (2.4 \pm 2.1)\%$

Compatible with expectation from Phys. Lett. B 774 (2017) 139

Results

LHCb-PAPER-2018-025 / PRELIMINARY



$$A_{CP}^{pK} = -0.020 \pm 0.013 \pm 0.019,$$
$$A_{CP}^{p\pi} = -0.035 \pm 0.017 \pm 0.020,$$

Systematic uncertainty	A_{CP}^{pK} [%]	$A_{CP}^{p\pi}$ [%]
Kaon or pion detection asymmetry	0.23	0.11
Proton detection asymmetry	0.67	0.67
PID asymmetry	0.74	0.73
Λ_b^0 production asymmetry	1.40	1.40
Trigger asymmetry	0.53	0.55
Signal model	0.02	0.02
Background model	0.23	0.47
PID efficiencies	0.57	0.74
Total	1.91	2.00

Main systematic cancels

$$\Delta A_{CP} \equiv A_{CP}^{pK^-} - A_{CP}^{p\pi^-}$$
$$0.014 \pm 0.021 \pm 0.013$$

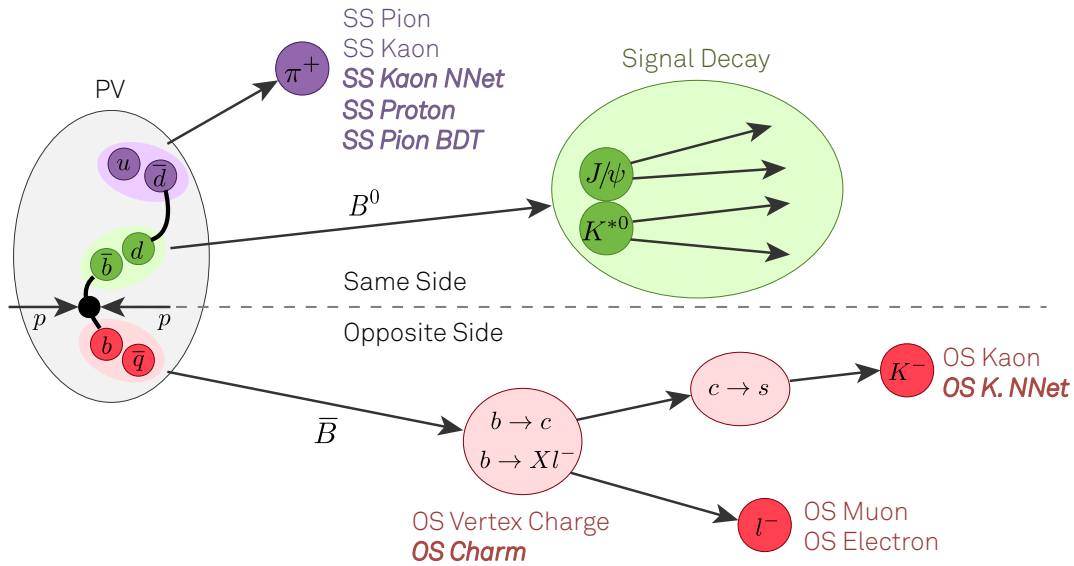
Error reduced by more than x4 with respect to CDF ☺

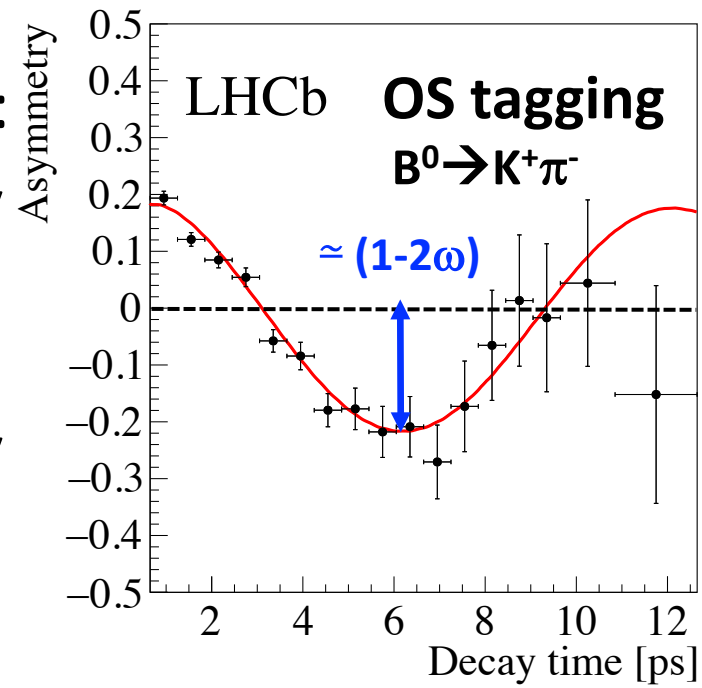
No evidence for CPV ☹

- A_p is determined weighting the result in Phys. Lett. B 774 (2017) 139 for signal kinematics

Flavour tagging

- In this analysis tagging is used on a per-event basis
  - **Opposite Side** (OS) taggers
  - **Same Side** (SS) taggers
    - **SSπ** and **SSp** for B^0
    - **SSK** for B_s^0
- Calibration of mistag fraction ω:
  - Use time-dependent asymmetry of $B^0 \rightarrow K^+\pi^-$ to calibrate OS, SSπ and SSp
  - Use time-dependent asymmetry of $B_s^0 \rightarrow D_s^-\pi^+$ to calibrate SSK

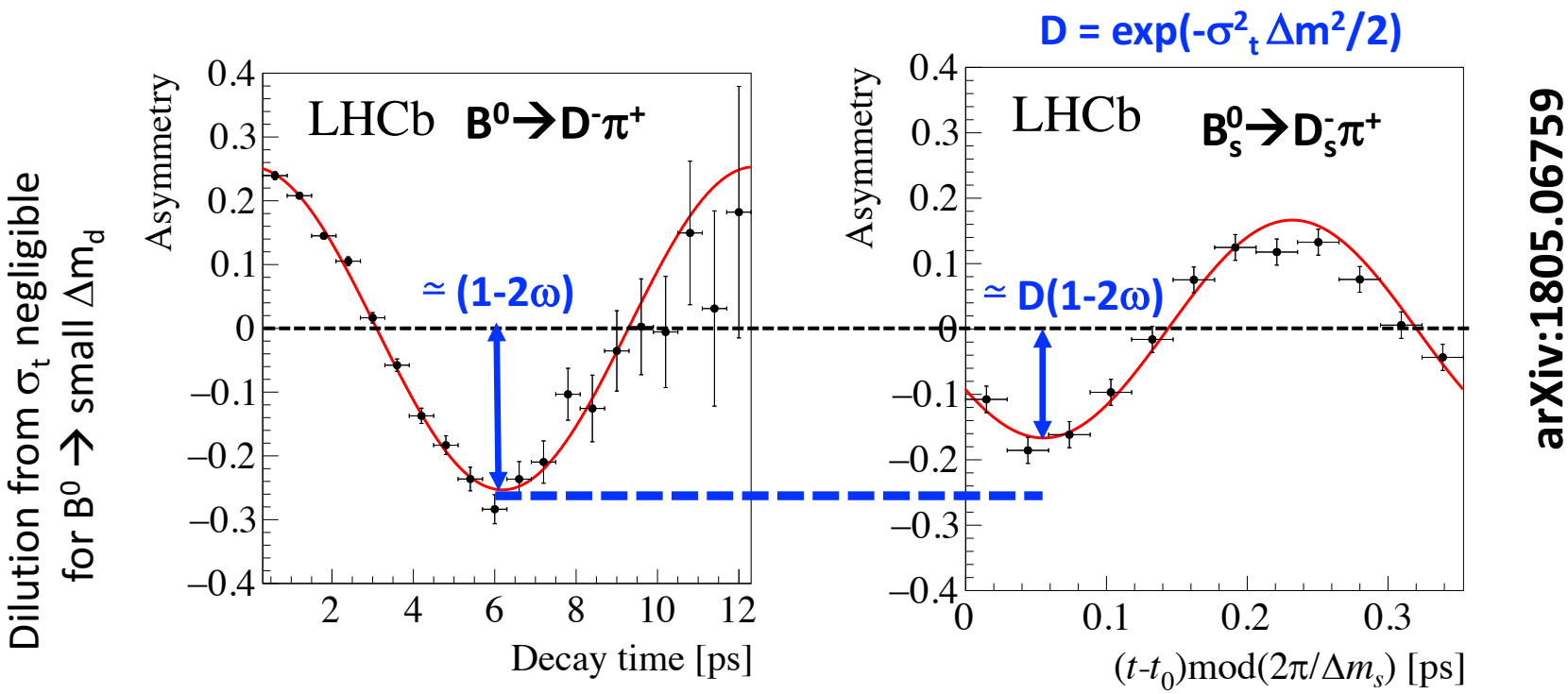




arXiv:1805.06759

Decay time resolution

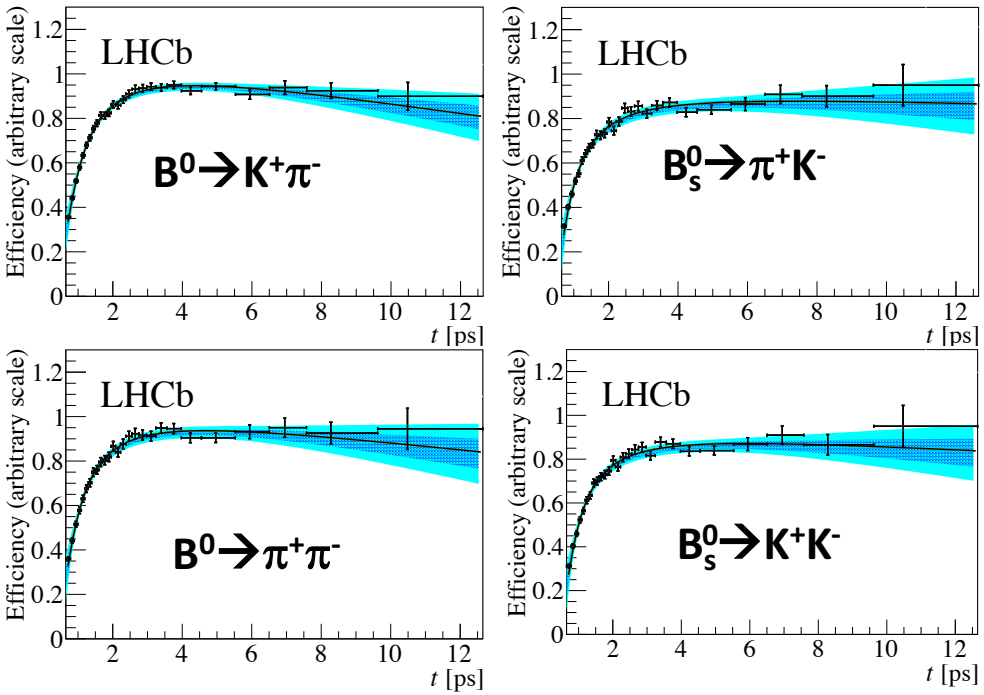
- Calibration is performed measuring simultaneously the time-dependent asymmetries of $B^0 \rightarrow D^-\pi^+$ and $B_s^0 \rightarrow D_s^-\pi^+$ decays
  - Dilution from flavour tagging calibrated thanks to $B^0 \rightarrow D^-\pi^+$
  - Additional dilution in the $B_s^0 \rightarrow D_s^-\pi^+$ decay allows to calibrate decay-time resolution
  - Portability from $B \rightarrow Dh$ to $B \rightarrow hh$ is studied on simulation



Decay-time acceptance

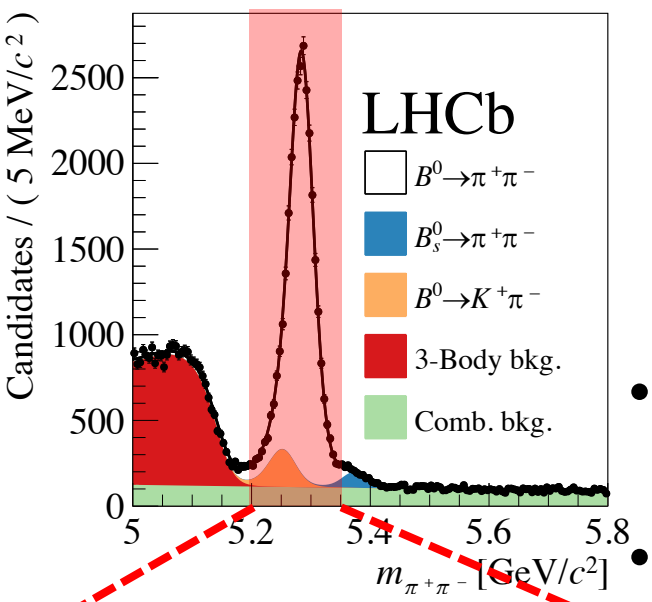
- Reconstruction efficiency as a function of decay-time is determined using $B^0 \rightarrow K^+\pi^-$ decays
  - Untagged decay rate of B^0 as a function of time is a pure exponential
  - For the other decay modes, simulation is used to study the differences

arXiv:1805.06759



Results

arXiv:1805.06759

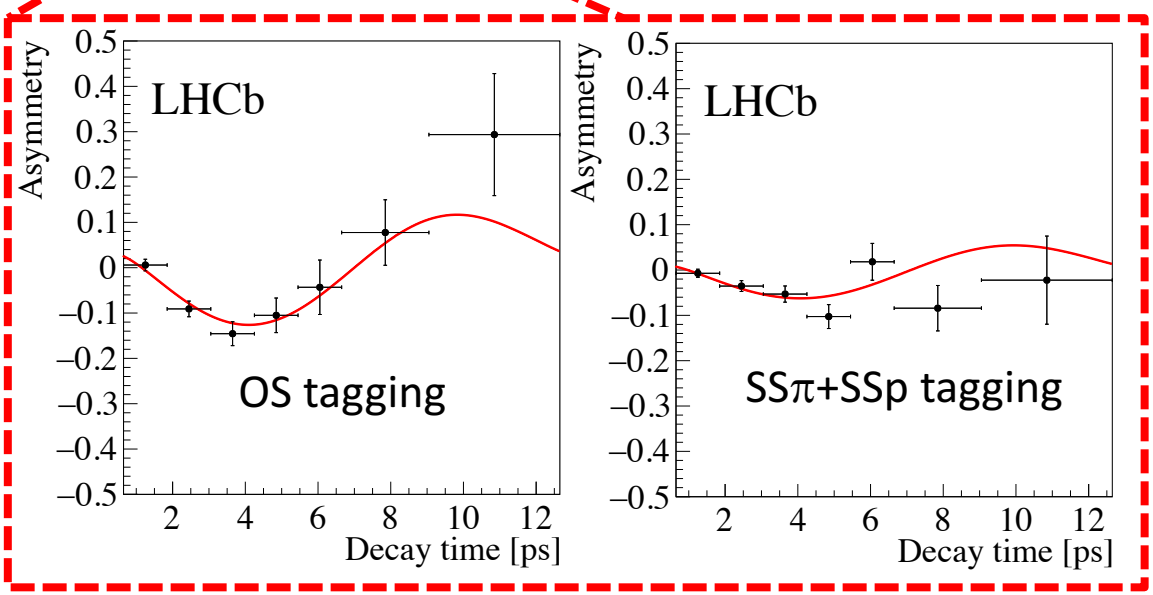


$$C_{\pi^+\pi^-} = -0.34 \pm 0.06 \pm 0.01$$

$$S_{\pi^+\pi^-} = -0.63 \pm 0.05 \pm 0.01$$

$\rho(C_{\pi\pi}, S_{\pi\pi}) = 0.448$

- Most precise from a single experiment
  - x2 better precision than previous LHCb
- Main syst.: cross-feed and 3-body model

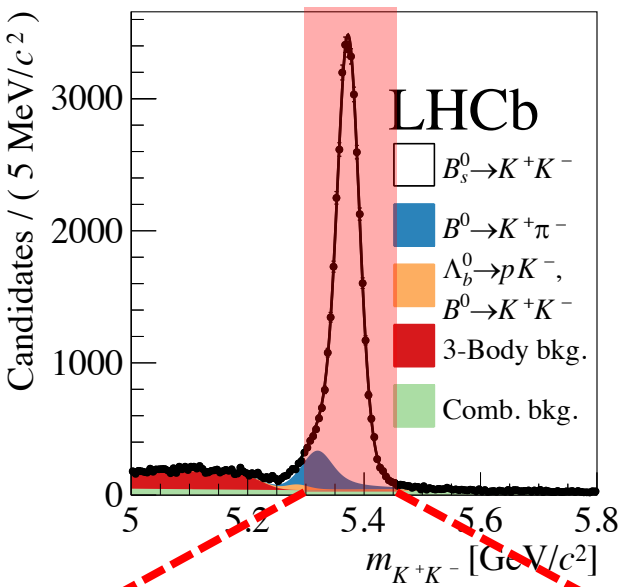


Fixed parameters

Parameter	Value
Δm_d	$0.5065 \pm 0.0019\,\mathrm{ps}^{-1}$
Γ_d	$0.6579 \pm 0.0017\,\mathrm{ps}^{-1}$
$\Delta\Gamma_d$	0
Δm_s	$17.757 \pm 0.021\ \mathrm{ps}^{-1}$
Γ_s	$0.6654 \pm 0.0022\,\mathrm{ps}^{-1}$
$\Delta\Gamma_s$	$0.083 \pm 0.007\ \mathrm{ps}^{-1}$
$\rho(\Gamma_s, \Delta\Gamma_s)$	-0.292

Results

arXiv:1805.06759

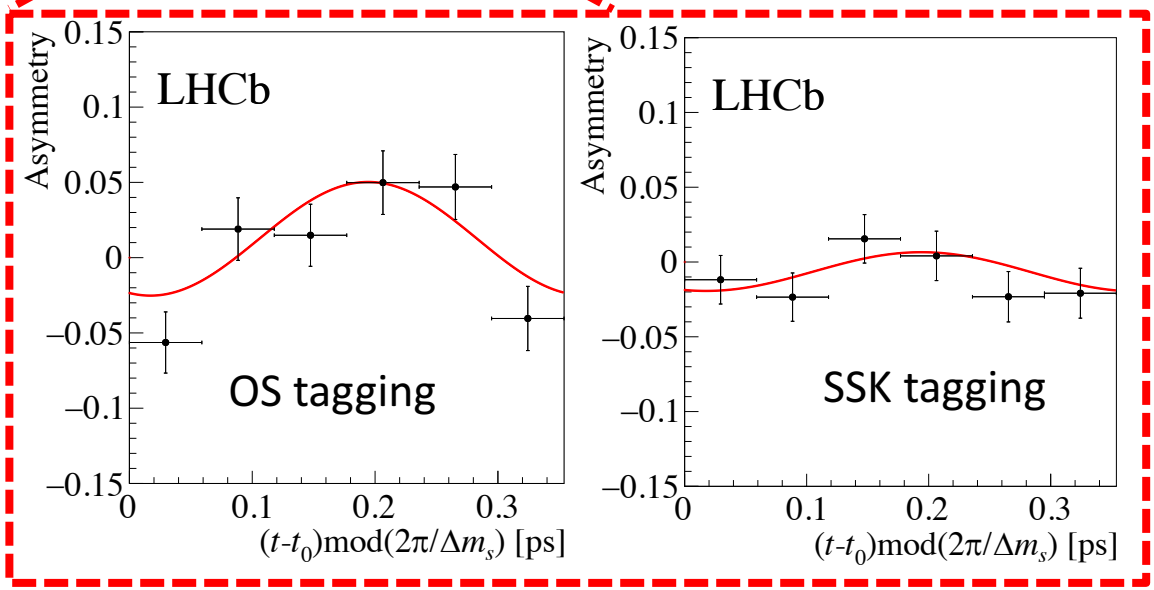


$$C_{K^+K^-} = 0.20 \pm 0.06 \pm 0.02$$

$$S_{K^+K^-} = 0.18 \pm 0.06 \pm 0.02$$

$$A^{\Delta\Gamma}_{K^+K^-} = -0.79 \pm 0.07 \pm 0.10$$

- Main syst.: decay-time resolution , decay time acceptance and input parameters
- First measurement of $A^{\Delta\Gamma}_{KK}$
- Strong evidence of CPV (~4σ) in $B^0_s \to K^+K^-$



Fixed parameters

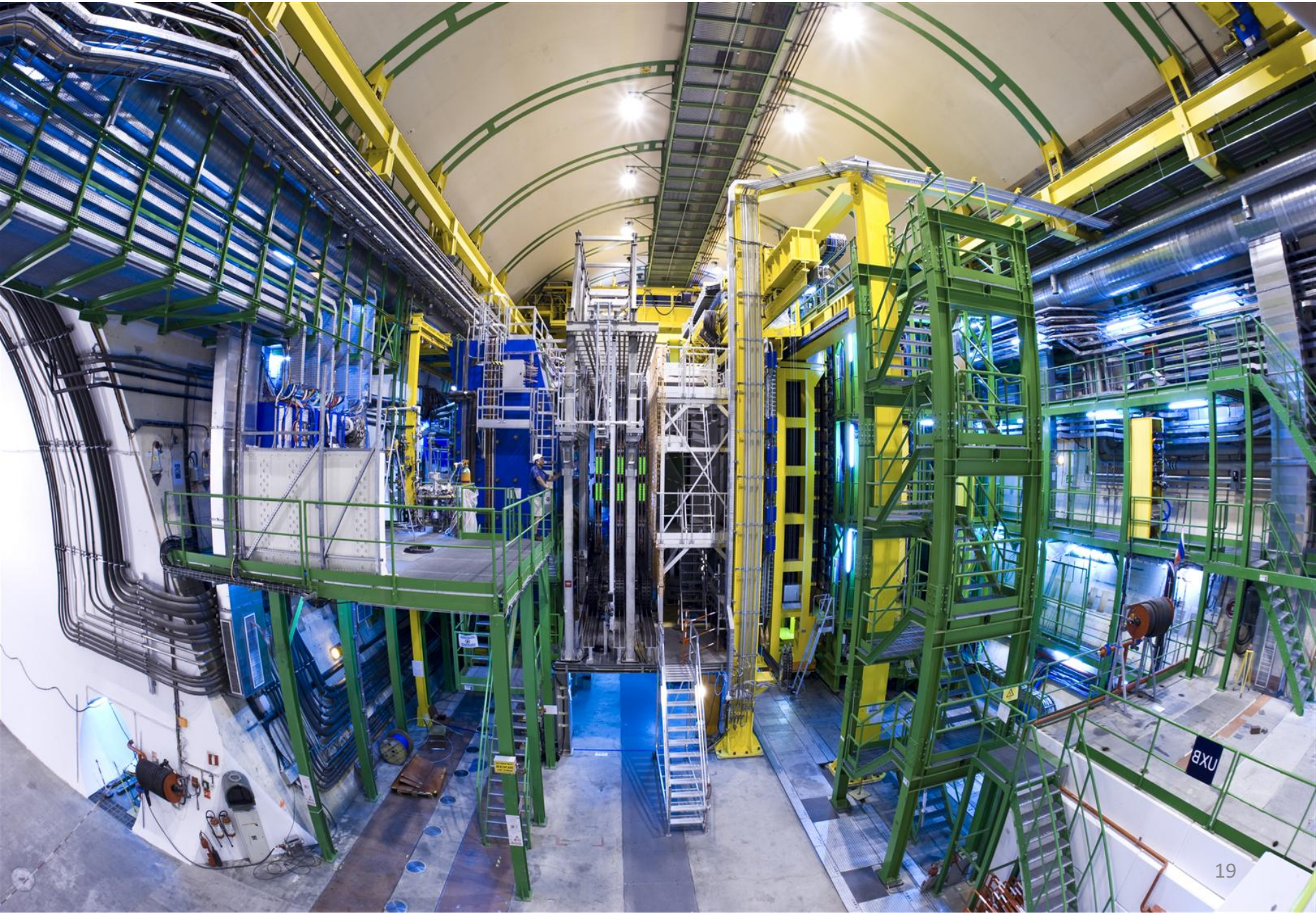
Parameter	Value
Δm_d	$0.5065 \pm 0.0019\,\mathrm{ps}^{-1}$
Γ_d	$0.6579 \pm 0.0017\,\mathrm{ps}^{-1}$
$\Delta\Gamma_d$	0
Δm_s	$17.757 \pm 0.021\ \mathrm{ps}^{-1}$
Γ_s	$0.6654 \pm 0.0022\,\mathrm{ps}^{-1}$
$\Delta\Gamma_s$	$0.083 \pm 0.007\ \mathrm{ps}^{-1}$
$\rho(\Gamma_s, \Delta\Gamma_s)$	-0.292

Conclusions

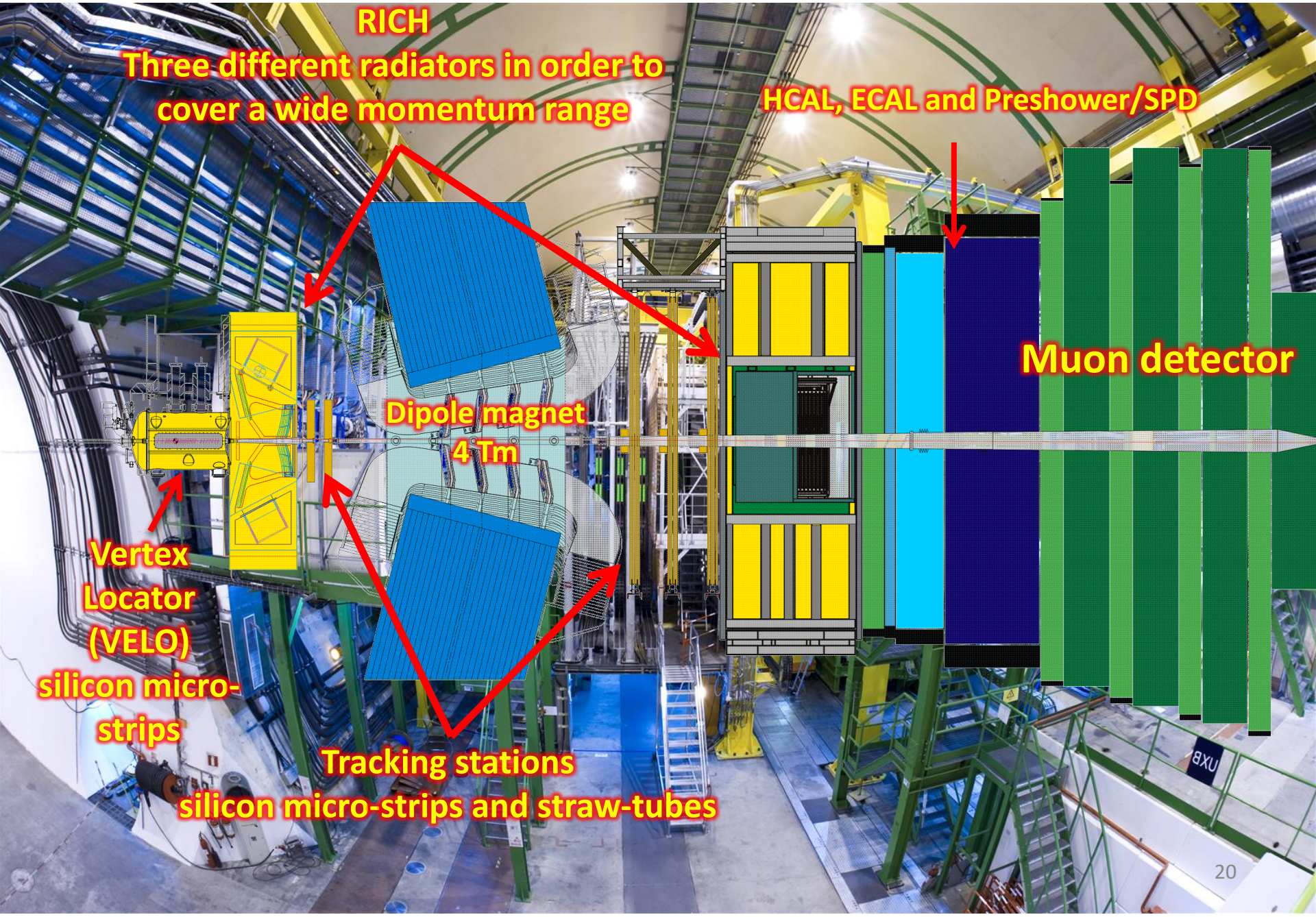
- The latest measurements of CPV in b-hadron decays to charmless charged two-body final states at LHCb have been presented
  - All the analyses are based on the full Run1 sample corresponding to 1 fb^{-1} @ 7 TeV and 2 fb^{-1} @ 8 TeV
- Significant improvement with respect to previous measurements for all the presented quantities
  - Best measurement of $C_{\pi\pi}$ and $S_{\pi\pi}$ from a single experiment
  - Strong evidence of CPV in $B_s^0 \rightarrow K^+K^-$ decay at 4σ
  - A_{CP} in $\Lambda_b^0 \rightarrow pK^-$ and $\Lambda_b^0 \rightarrow p\pi^-$ have precisions 4 times better than previous measurement from CDF
  - No evidence of deviations from the SM
- Already x3 statistics is available from Run2

Backup

The LHCb detector

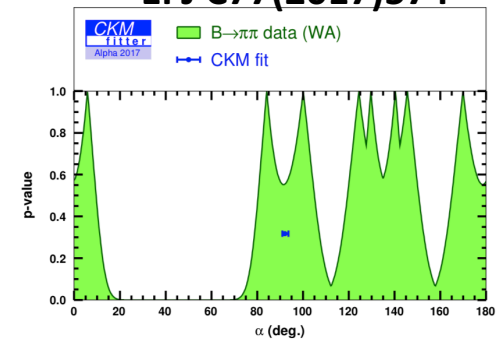


The LHCb detector

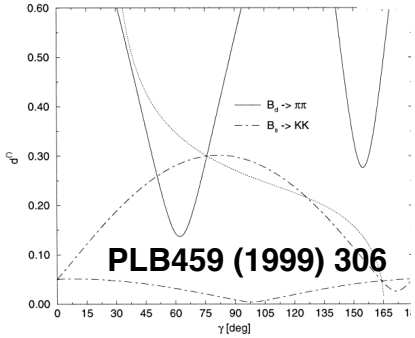


How to exploit $H_b \rightarrow h^+h'^-$ decays

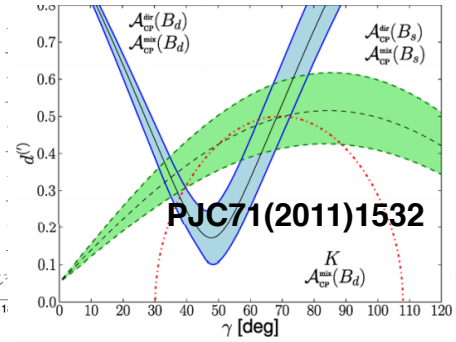
EPJ C77(2017)574



- CP asymmetries of $B^0 \rightarrow \pi^+\pi^-$
  - fundamental input to the isospin analysis to determine the CKM angle a
- First proposal to include also $B_s \rightarrow K^+K^-$ decays dates back to 1999
  - exploiting U-spin symmetry to constraint QCD uncertainties and determine γ and $-2\beta_s$



PLB459 (1999) 306



PJC71(2011)1532

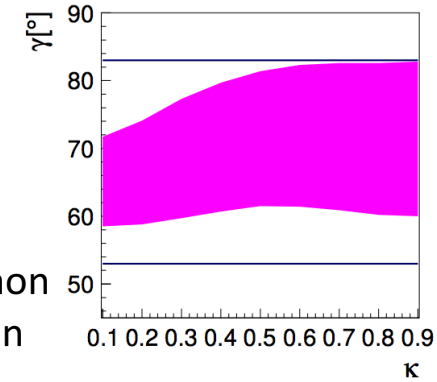
- A_{CP} of $B^0 \rightarrow K^+\pi^-$ and $B_s \rightarrow \pi^+K^-$ provide a test of the SM assuming U-spin symmetry

$$\Delta = \frac{A_{CP}^{B^0}}{A_{CP}^{B_s^0}} + \frac{\mathcal{B}\left(B_s^0 \rightarrow \pi^+K^-\right)}{\mathcal{B}\left(B^0 \rightarrow K^+\pi^-\right)}\frac{\tau_d}{\tau_s} = 0$$

PLB621(2005)126

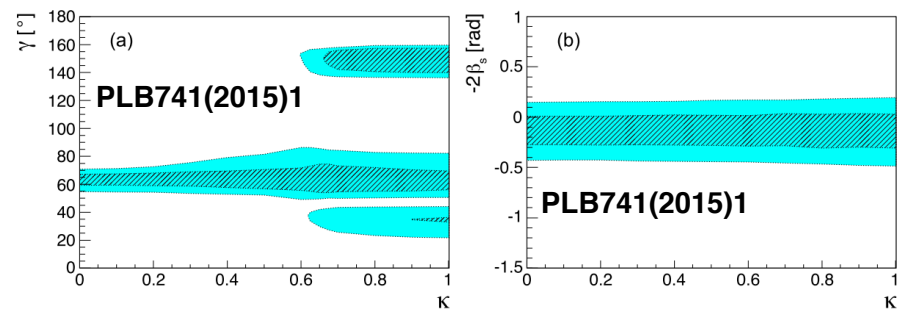
How to exploit $H_b \rightarrow h^+h'^-$ decays

JHEP 10 (2012) 029



- More recent studies aimed to reduce the impact of the uncertainty due to U-spin breaking
  - Combined analysis of $B^{0,\pm} \rightarrow \pi^{0,\pm}\pi^{0,\pm}$ and $B_s \rightarrow K^+K^-$

κ = allowed level of non factorizable U-spin breaking



- Combining CP asymmetries

in $B^0 \rightarrow \pi^+\pi^-$ and $B_s \rightarrow K^+K^-$

with information from semileptonic $B^0 \rightarrow \pi\ell\nu$ and

$B_s \rightarrow K\ell\nu$ allow to reduce the usage of U-spin symmetry

[arXiv:1608.00901,arXiv:1612:07342]

Systematic uncertainties

arXiv:1805.06759

Source of uncertainty	$C_{\pi^+\pi^-}$	$S_{\pi^+\pi^-}$	$C_{K^+K^-}$	$S_{K^+K^-}$	$A^{\Delta\Gamma}_{K^+K^-}$	$A^{B^0}_{CP}$	$A^{B^0_s}_{CP}$
Time-dependent efficiency	0.0011	0.0004	0.0020	0.0017	0.0778	0.0004	0.0002
Time-resolution calibration	0.0014	0.0013	0.0108	0.0119	0.0051	0.0001	0.0001
Time-resolution model	0.0001	0.0005	0.0002	0.0002	0.0003	negligible	negligible
Input parameters	0.0025	0.0024	0.0092	0.0107	0.0480	negligible	0.0001
OS-tagging calibration	0.0018	0.0021	0.0018	0.0019	0.0001	negligible	negligible
SSK-tagging calibration	—	—	0.0061	0.0086	0.0004	—	—
SSc-tagging calibration	0.0015	0.0017	—	—	—	negligible	negligible
Cross-feed time model	0.0075	0.0059	0.0022	0.0024	0.0003	0.0001	0.0001
Three-body bkg.	0.0070	0.0056	0.0044	0.0043	0.0304	0.0008	0.0043
Comb.-bkg. time model	0.0016	0.0016	0.0004	0.0002	0.0019	0.0001	0.0005
Signal mass model (reso.)	0.0027	0.0025	0.0015	0.0015	0.0023	0.0001	0.0041
Signal mass model (tails)	0.0007	0.0008	0.0013	0.0013	0.0016	negligible	0.0003
Comb.-bkg. mass model	0.0001	0.0003	0.0002	0.0002	0.0016	negligible	0.0001
PID asymmetry	—	—	—	—	—	0.0025	0.0025
Detection asymmetry	—	—	—	—	—	0.0014	0.0014
Total	0.0115	0.0095	0.0165	0.0191	0.0966	0.0030	0.0066